9-2019

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Abstract

Trunk kinematic variables have been used to understand the risk of low back injuries in the workplace. Variability in the trunk kinematics as an individual performs a repetitive lifting task is an underexplored area of research. In the current study, it was hypothesized that workplace variables (starting height of lift and load weight) would have an impact on the variance in the kinematic and kinetic variables. Twenty participants performed 60 repetitions of an asymmetric lifting task under four different conditions representing two levels of load weight (5% or 10% of the participant's body weight) and two levels of starting height (80% or 120% of the participant's knee height). The Lumbar Motion Monitor was used to capture trunk kinematic variables from the concentric range of lifting motion while ground reaction forces were collected using a force platform. The primary dependent variables were the variance of kinematic and kinetic variables across these 60 repetitions. The results showed a significant effect of starting height on the variance of sagittal plane trunk kinematics with the lower starting height generating an increased variance (sagittal range of motion increased by 55%, average sagittal velocity increased by 95%, peak sagittal velocity increased by 105%, and peak sagittal acceleration increased by 130%). There was no consistent significant main effect of either independent variable on the variance of the transverse plane kinematics. Additionally, there was no significant effect of load weight on the variance of any trunk kinematic variables tested. In terms of ground reaction forces, it was shown that the starting height of the load had a significant effect on the variance of peak vertical ground reaction force, while the weight of the load had a significant effect on the variance of the peak shear force.

Keywords

Manual material handling, Lifting kinematics variability

Disciplines

Biomechanics and Biotransport | Ergonomics | Industrial Engineering

Comments

This is a manuscript of an article published as Norasi, Hamid, Jordyn Koenig, and Gary A. Mirka. "The effects of load weight and load starting height on variability of lifting kinematics and kinetics." *International Journal of Industrial Ergonomics* 73 (2019): 102830. DOI: 10.1016/j.ergon.2019.102830. Posted with permission.

The Effects of Load Weight and Load Starting Height on Variability of Lifting Kinematics and Kinetics

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Declaration of interest: 'Declarations of interest: none'.

Abstract

Trunk kinematic variables have been used to understand the risk of low back injuries in the workplace. Variability in the trunk kinematics as an individual performs a repetitive lifting task is an underexplored area of research. In the current study, it was hypothesized that workplace variables (starting height of lift and load weight) would have an impact on the variance in the kinematic and kinetic variables. Twenty participants performed 60 repetitions of an asymmetric lifting task under four different conditions representing two levels of load weight (5% or 10% of the participant's body weight) and two levels of starting height (80% or 120% of the participant's knee height). The Lumbar Motion Monitor was used to capture trunk kinematic variables from the concentric range of lifting motion while ground reaction forces were collected using a force platform. The primary dependent variables were the variance of kinematic and kinetic variables across these 60 repetitions. The results showed a significant effect of starting height on the variance of sagittal plane trunk kinematics with the lower starting height generating an increased variance (sagittal range of motion increased by 55%, average sagittal velocity increased by 95%, peak sagittal velocity increased by 105%, and peak sagittal acceleration increased by 130%). There was no consistent significant main effect of either independent variable on the variance of the transverse plane kinematics. Additionally, there was no significant effect of load weight on the variance of any trunk kinematic variables tested. In terms of ground reaction forces, it was shown that the starting height of the load had a significant effect on the variance of peak vertical ground reaction force, while the weight of the load had a significant effect on the variance of the peak shear force.

Relevance to industry

A relationship between trunk kinematics and risk of injury has been previously demonstrated. Investigating the variability of these trunk kinematics parameters in a repetitive lifting task and its relation with workplace parameters can provide an understanding of how changing workplace parameters may affect the risk of low back problems.

Keywords: Manual Material Handling, Lifting Kinematics Variability

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

INTRODUCTION

Low back pain (LBP) is a prevalent health problem in the United States and worldwide (Hoy et al., 2012; Murphy et al., 2017). Low back disorders (LBDs) are recognized as a major musculoskeletal disorder leading to work absenteeism and physicians' care in the United States and throughout the world (Praemer et al., 1992; Hoy et al., 2014). Individuals, their families, industries, and government are all affected by LBP (Hoy et al., 2010). It has been estimated that in 1998 almost $91 billion was spent directly on back pain health-care in the United States (Luo et al., 2004). It has been estimated that in 1995 almost $9 billion was spent on occupational LBP claims in the United States and the incidence rate was 1.8 per 100 (Murphy and Vollin, 1999). It is widely believed that the majority of occupational LBP cases are associated with manual material handling (MMH) such as lifting - even with the increased use of automation (Dempsey and Hashemi 1999). Many studies have investigated different facets of manual material handling and its effect on LBP (e.g. Andersen et al., 2017; Brandt et al., 2018; Varrecchia et al., 2018).

A number investigations have sought to identify workplace parameters that lead to LBP and low back injuries (e.g. Chaffin and Park, 1973; Allread et al., 1996; Davis and Marras, 2000; Hoogendoorn et al., 2002; Ngo et al., 2017; Asadi et al., 2019; Labaj et al., 2019). According to a systematic review by Nelson and Hughes (2009), association between mass lifted and back injuries was found in most studies that investigated this factor, while awkward postures and highly repetitive lifting motions were also identified (Nelson and Hughes, 2009). Using a different methodology, Marras et al. (1993, 1995, 1999) examined associations between low back kinematics and low back injuries. Lumbar Motion Monitor (LMM) was used to derive the position, velocity and acceleration of the lumbar spine in sagittal, transverse, and coronal planes in a large sample of industrial workers. Using multiple logistic regression, these authors demonstrated that a combination of five parameters could be used to distinguish between high and low risk jobs. These parameters were: load moment, lifting frequency, lateral trunk velocity, twisting trunk velocity, and sagittal flexion angle (Marras et al., 1993, 1995, 1999). Noting that three of the five predictor variables are related to the kinematic profile utilized by the lifter, it is worthwhile to further explore this aspect of occupational human performance. One particular aspect of these trunk kinematic profiles that has not been fully explored is the amount of variability in these kinematic characteristics during a repetitive lifting task.

The multi-joint system of the human body provides the opportunity for variability in the motions/moments generated by the various joints in the kinematic chain. A particular lifting task may be found to be safe according to a risk assessment method, but the variability in the technique (both inter-lifter and intra-lifter variability) demonstrate that a significant percentage of the lifts performed may place the lifter at risk. In an early study by Mirka and Marras (1993), it was hypothesized that biomechanical variability may affect the relative number of lifts which may exceed the recommended tissue tolerances (Mirka and Marras, 1993). Further, it is conceivable that adjusting a workplace parameter to decrease the mean value of a low back stressor, could increase the variability of that stressor, thereby increasing the risk that more exertions exceed the tissue limits (Granata et al., 1999). In another study, Mirka and Baker (1996) evaluated the variability of human performance during lifting task by utilizing a biomechanical model to calculate the sagittal moment about L5/S1 and exploring the variability of magnitude of the peak sagittal moment. The detailed results with respect to the effects of the load weight on the variability of kinematic parameters in sagittal plane were not presented, but these authors did demonstrate an increase in the variability of the peak net sagittal moment with increasing load magnitude (Mirka and Baker, 1996). Granata et al. (1999) showed that spinal load can change significantly trial-to-trial during a task without changing any requirement or workplace parameter. In their study, these authors utilized an EMG-assisted biomechanical model to assess spinal loading and used intra-class correlations to explore the inter- and intra-subject variability in the estimates of spinal loads. These authors noted that the subject-to-subject differences generated the greatest source of variability, and that the variability in these estimates of spinal loads can be affected by workplace factors such as the box weight, asymmetry, and worker experience. They noted that much of the variability in the lifting moments and spine reaction forces could be traced back to the lifting kinematics strategy chosen by the lifter (Granata et al., 1999).

Quantifying the variability of lifting kinematics chosen during a free-dynamic lifting task and assessing the relationship between workplace parameters and the magnitude of this variability may provide researchers with a deeper understanding of how workplace modifications may impact the risk of LBD. In this study, the effects of load weight and lift starting height on the variance of sagittal and transverse plane kinematic variables were explored. It was hypothesized that a lower stating height and a greater load would increase the variance of these trunk kinematic characteristics in both planes.

MATERIAL AND METHODS

2.1. Participants

Ten male and ten female participants were recruited for this study. Participants were screened for history of chronic back injuries or current pain in their neck, shoulders, hip or knee joints. The average ± standard deviation for several anthropometric characteristics are as follows: age 26 ± 3 years, stature172.4 ±9.6 cm, standing elbow height 110.6 ± 6.2 cm, standing knee height 50.5 ± 4.1 cm, and weight 70.7 ±11.5 kg.

2.2. Apparatus

2.2.1 Data Collection Instrumentation

The Lumbar Motion Monitor (LMM) (Chattanooga Group Inc., TN) was used to monitor the motion of the participant's lower back during the concentric lifting phase of a box transfer task. The device captures the 3-D angular position at a rate of 60 Hz and derives angular velocity and angular acceleration in sagittal, transverse, and coronal planes. A Bertec force platform (Model FP6090-PT Bertec Corporation, Columbus OH, USA) was used to collect the ground reaction forces and moments during the experiment. The force platform data was collected at a rate of 10 Hz.

2.2.2 Lifting Task Apparatus

The load lifted in this study was a plastic crate filled with water bottles. The crate was 33 cm (width) x 33cm (depth) x 29 cm (height). The weight of the load was 5% and 10% of the participant's body weight. The participants' task was to lift the crate from a skate wheel conveyor system, then rotate 90 degrees and place it on another conveyor. Under a given condition, the starting height of the lift was either 80% or 120% of their knee height while the ending height of the lift was their standing elbow height (Figure 1).

Figure 1. Apparatus and lifting task: (a) starting position and (b) ending position.

2.3. Experimental Design

2.3.1. Independent Variables

The independent variables in this experiment were the starting height of the lift and the weight of the load. These variables were standardized to the anthropometry of the individual participant in order to standardize the task across participants: 5% and 10% of the participant's body weight was used for the weight of the load (W5% and W10%, respectively) and 80% and 120% of the participant's knee height was used for the starting height of the lift (H80% and H120%, respectively).

2.3.2. Dependent Variables

The dependent variables in this experiment were the values of variance of trunk kinematics variables in sagittal and transverse planes and the values of variance of the peak vertical and shear (combination of anterior-posterior and lateral) ground reaction forces during the concentric lifting motion. The concentric lifting phase was determined to be that region of the collected data, wherein the load was fully supported in the hands. The specific dependent variables were the variance of 1) sagittal plane range of motion (SROM), 2) average sagittal plane velocity (SVEL), 3) peak sagittal plane velocity (SVELM), 4) peak sagittal plane acceleration (SACC), 5) transverse plane range of motion (TROM), 6) average transverse plane velocity (TVEL), 7) peak transverse plane velocity (TVELM), 8) peak transverse plane acceleration (TACC), 9) peak vertical ground reaction force (Fv) and 10) peak horizontal shear force (Fxy).

2.4. Experimental Tasks

The experiment was explained to the participant and an informed consent document was signed. After a five-minute warmup, the participant donned the Lumbar Motion Monitor and the participant was led to the force platform and asked to choose a comfortable lifting stance and this position was marked using tape. They were asked to maintain the same position of the feet during the experiment. The experimenter released the crate from the endpoint of the first conveyor at the designated time interval. The lifting rate was standardized at 6 lifts/minute. No specific instructions for lifting was given to the participants. They were simply asked to lift the load from the first conveyor and place the load on the second conveyor (Figure 1).

The four trials (each combination of level of starting height and load weight) each lasted ten minutes with five minutes of rest between each trial. The presentation order of these four trials was randomized for each participant. After the fourth trial the participant performed a five-minute cool down and stretching exercise and was free to leave.

2.5. Data Processing

The required dependent variables during the concentric lifting phase were extracted from each lifting motion. To allow the analysis to focus intra-participant variability the data were centered so that the average value for all participants within a condition was equal. This was accomplished by adding the difference between the overall mean and a participant's mean to the individual observations.

$$NX_{ijk}=X_{ijk} + (Y_{i..}-y_{ij.}) \quad (1)$$

Where: i= the number of the condition=1, 2, 3, 4

j= the number of the participant=1, 2, …, 20

k=the number of the replication=1, 2, …, 60

Where NX is the normalized data point; the X is the original, collected value; Y is the grand average of the corresponding kinematic parameter in Condition i and y is the average in that Condition i for Participant j. These centered data were then used to calculate the variance for each of the four experimental conditions thereby controlling for the inter-participant variability.

The force platform data for the fourth participant was lost, so ground reaction force data for only 19 participants' data were used in these calculations.

2.6. Statistical Analysis

SAS 9.4 was used for statistical analysis. Levene's test was used to evaluate equality of variances across the four conditions. To further assess any statistically significant differences, pair-wise comparisons using Levene's test were also conducted. A Bonferroni correction was applied to control for the experiment-wise error rate ($\alpha=0.0083$) thereby maintaining an overall alpha level of 0.05.

RESULTS

Statistically significant differences in variances were found for all four of the sagittal plane variables (Table 1), but there were no statistically significant differences in the variances of the transverse plane variables except for peak transverse plane velocity (TVELM). Pair-wise comparisons were used to further investigate the significant differences in variances of sagittal plane variables caused by different levels of load weight and starting height, while no further evaluation was done for transverse plane variables except for TVELM. The results of the pair-wise comparisons in sagittal plane demonstrate that the starting height had a statistically significant impact on the variance in the sagittal plane variables across conditions ($p<0.0001$). These significant effects are shown graphically in Figures 2-5. The distributions associated with the sagittal range of motion, average sagittal velocity, peak sagittal velocity, and peak sagittal acceleration data are shown in Figures 6-9. These figures help to visualize the nature of these effects. The pair-wise comparison for TVELM revealed that the only significant difference occurred when the high load-low starting height condition (variance 53.0 $(deg/sec)^2$) was compared with low load-high starting height condition (variance 41.2 $(deg/sec)^2$) ($p=0.0011$).

Variable	SROM	SVEL	SVELM	SACC	TROM	TVEL	TVELM	TACC
P-value	<0.0001	<0.0001	<0.0001	<0.0001	0.7249	0.2162	0.0077	0.2113

Table 1. P-values from Levene's Test for homogeneity of variances for trunk kinematic variables

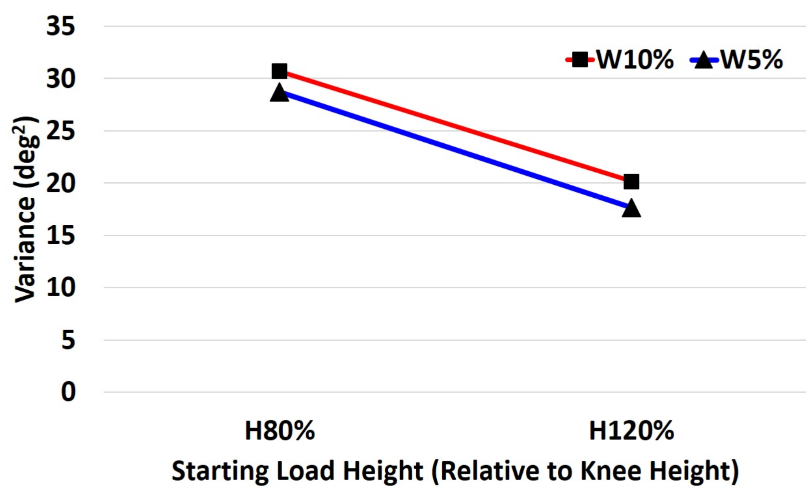

Figure 2. Variance of sagittal range of motion (SROM) as a function of load weight and starting height of load.

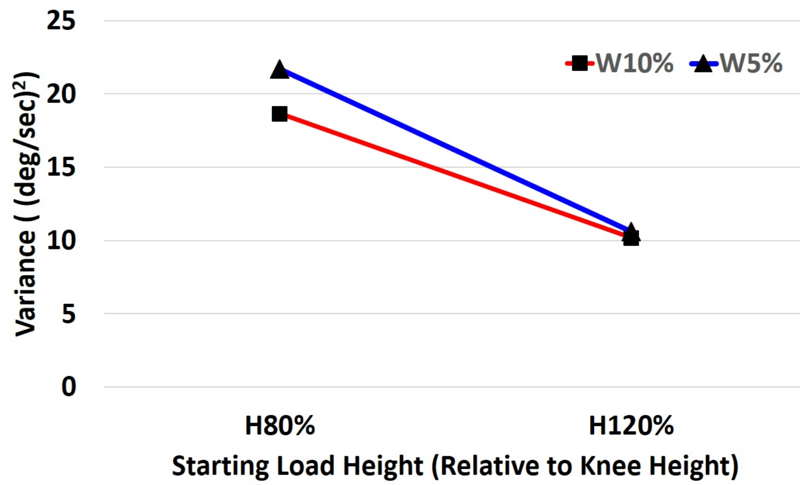

Figure 3. Variance of average sagittal velocity (SVEL) as a function of load weight and starting height of load.

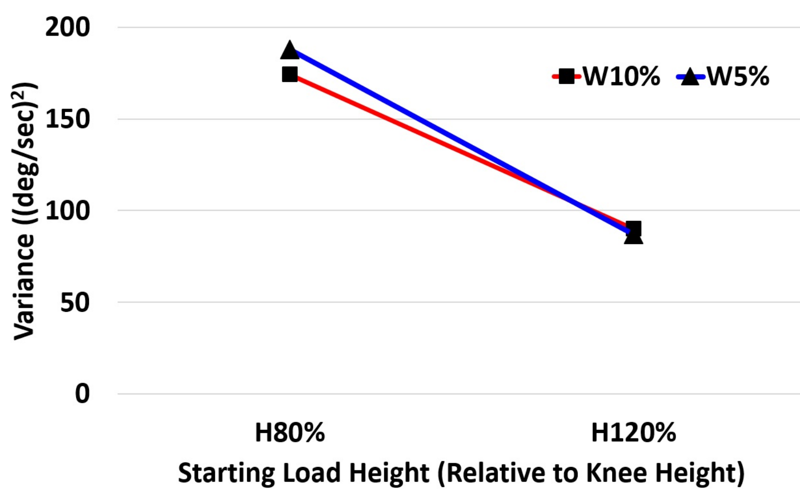

Figure 4. Variance of peak sagittal velocity (SVELM) as a function of load weight and starting height of load.

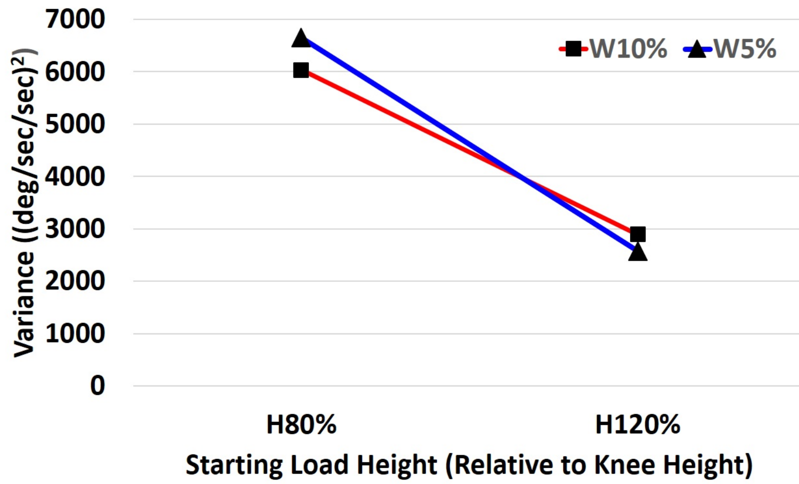

Figure 5. Variance of peak sagittal acceleration (SACC) as a function of load weight and starting height of load.

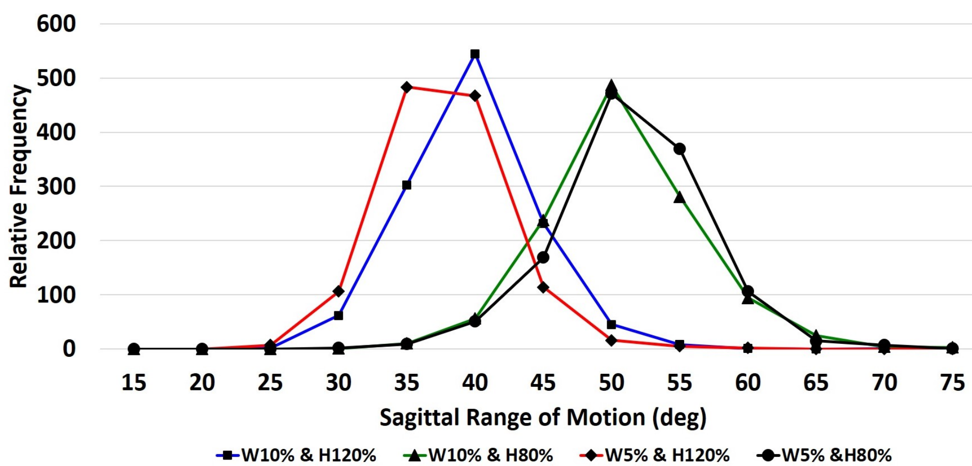

Figure 6. Distributions of sagittal range of motion (SROM).

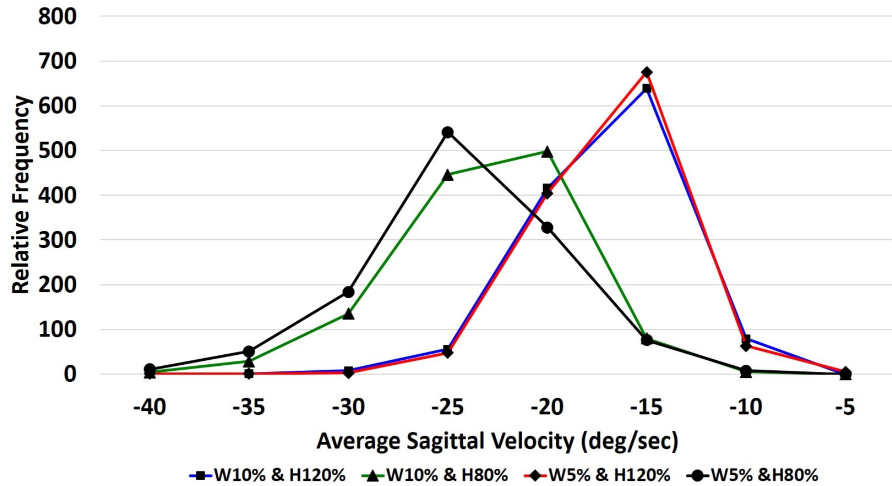

Figure 7. Distributions of average sagittal velocity (SVEL). Negative values on x axis reflect the fact that it is going from more flexed postures to less flexed postures.

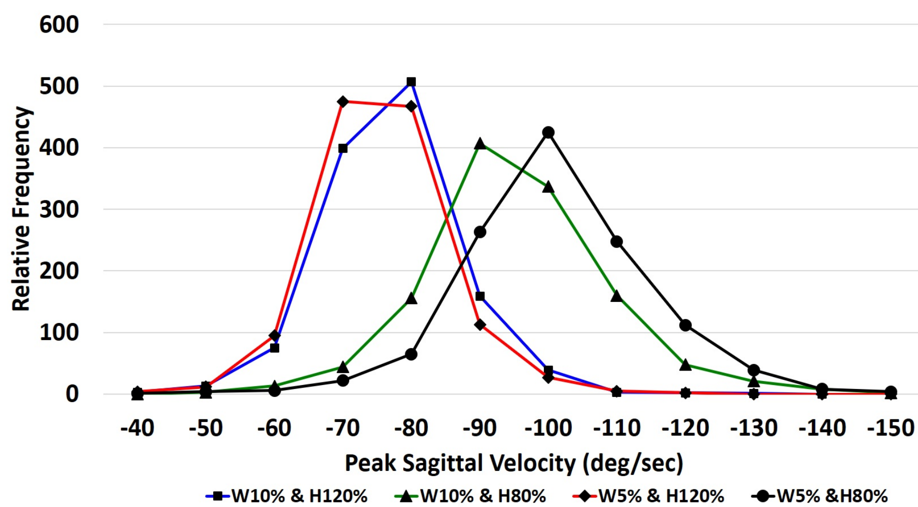

Figure **8**. Distributions of peak sagittal velocity (SVELM). Negative values on x axis reflect the fact that it is going from more flexed postures to less flexed postures.

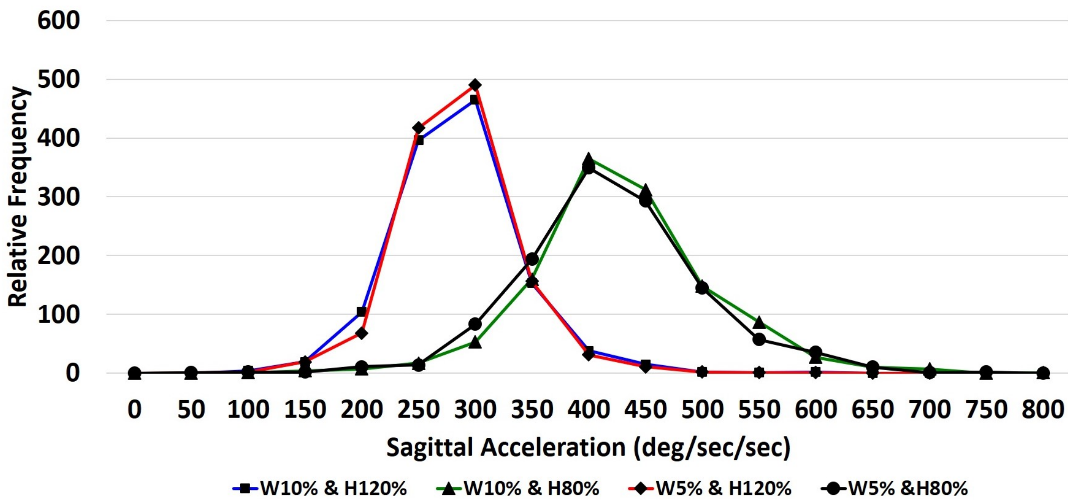

Figure 9. Distributions of peak sagittal acceleration (SACC).

For the force platform data, statistically significant differences in variances were found for both variables (Fv) and (Fxy). Pair-wise comparisons were used to investigate these differences in more details. The force platform data showed that for the variance of the peak vertical ground reaction force (Fv) the dominant factor is the starting height of the load ($p<0.0001$), while for the variance of the maximum horizontal force (Fxy) the dominant factor is the weight of the load ($p<0.0003$). These significant effects are shown graphically in Figures 10-11.

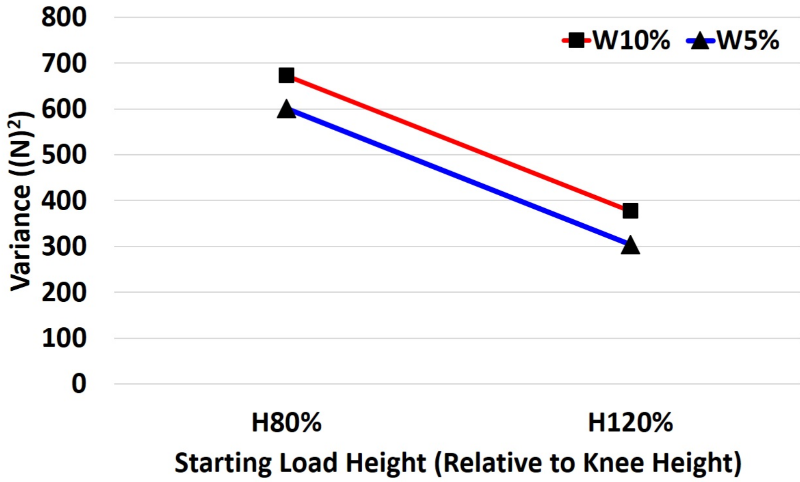

Figure 10. Variance of peak vertical force (Fv) as a function of load weight and starting height of load.

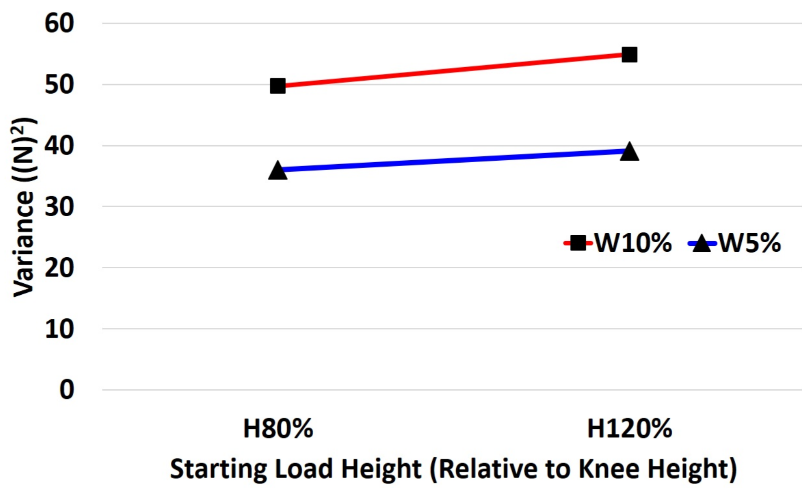

Figure 11. Variance of peak horizontal force as a function of load weight and starting height of load.

DISCUSSION

The aim of this study was to investigate the effects of the load weight and starting height on the variability of lifting kinematics and ground reaction forces in a repetitive lifting task. It was hypothesized that the variability of lower back kinematics would increase with greater load and lower starting height. Strong evidence was found to confirm that changing the starting height of the load impacts the variance of the kinematic parameters in sagittal plane but not the transverse plane. Contrary to the original hypotheses, the results did not show a significant effect of weight of the load on the variability of any of the kinematic parameters assessed: when the starting height of the box was held constant, changing the weight of the box had no significant impact on the variance of any of the kinematic variables considered in this study. This result is inconsistent with the findings of Granata et. al. (1999). In this previous study, it was found that increasing box weight significantly decreased the variability of velocities and accelerations in sagittal plane (Granata et al., 1999). An explanation for this inconsistency may lie in the differences in the magnitude of the loads used in the two studies. In the current study the difference between 5% and 10% of body weight may have failed to generate statistically significant differences shown in the previous study when the loads were 13.6 and 27.3 kg (significantly larger than the highest loads seen in the current study). Future studies should seek to refine some of these load-related topics. There was on significant effect in the transverse plane and that was on the peak transverse velocity. The results showed that only when the weight of the load increased and the starting height of the load decreased simultaneously, the variance of TVELM increased significantly (~25%). This finding would indicate that the more challenging lifting task generated greater variance in this kinematic variable.

In the current study, it was reasoned that standardizing the weight relative to the mass of the participant would allow for a clearer analysis of the intra-participant variance but evaluation of inter-participant variance with standard weights can likewise provide insights into realistic working conditions. On the other hand, only when the weight of the load increased and the starting height of the load decreased simultaneously, the variance of TVELM increased significantly. This finding propounds evidence for the effect of the weight of the load on the variance of lifting kinematics. Future studies may provide researchers with more details about these associations.

An important point to note is that the changes in the mean and the variability of kinematic parameters are not always positively correlated. Future studies can reveal how the mean values and the variability of the risk factors for LBPs may change by changing workplace parameters. This could make these findings more practical regarding ergonomic interventions. Modifying a workplace parameter may decrease the average value of a risk factor, but it may increase its variability at the same time. This concept may necessitate more cautious actions regarding ergonomic interventions. In general, modifying a workplace parameter can influence the magnitude and the variability of a measure in different ways. Therefore, quantifying how both the mean and variance of a response variable change as a function of workplace variables may provide valuable insights that can be used to reduce the risk of low back injuries. While a negative view of variability is presented in this paper, there are those, current authors included, that note that there are positive effects of variability that must be considered. Variability in muscle activation profiles that can bring relief during static, fatiguing exertions and variability in multi-joint kinematic systems where the stresses can be more equitably distributed during a repetitive task are two such examples. When it comes to single joint kinematic variables, however, variability is viewed negatively as it increases the risk of high stress conditions.

The ground reaction forces during lifting have been evaluated in past studies. In a study by Shin et al. (2006) it was found that the destination height and asymmetry affect the peak horizontal ground reaction forces during lifting (Shin et al., 2006). Also, it has been shown that there are associations between the peak vertical ground reaction force and lifting speed, box weight and the interaction between these two factors during squat lifting. The peak value of vertical ground reaction force increased with increment in the speed of lifting. Increment in the box weight increased the peak vertical ground reaction force too (Vahdat and Tabatabai Ghomshe, 2018). Variability in ground reaction forces is much less well understood in the lifting literature. Variability of ground reaction forces have been investigated in gait research as one of the possible factors related to falling, smooth walking and stability. Masani et al. (2002) evaluated the effects of speed on variability of ground reaction forces during walking on treadmills using coefficients of variation. It was found that the variability of the peak values of ground reaction force in vertical and mediolateral directions increased as the walking speed increased, while for the ground reaction force in anteroposterior direction an optimal speed was found in which the variability was minimum (Masani et al., 2002). The force platform data in the current study revealed the effects of the weight of the load and the starting height of the load on the ground reaction forces during a repetitive lifting task. Analysis of the force platform data showed that the starting height of the load has a significant impact on the variance of the peak vertical ground reaction force, while the weight of the load was shown to significantly affect the variability of the maximum shear force at the foot ground interface.

There are several limitations to the generalizability of the results of the current study. First, the participants in this study were healthy young persons with no chronic back problems with limited experience in professional manual materials handling. The controlled laboratory in which this experiment was conducted also poses a limitation. Realistic work conditions may provide more opportunity for varied lifting technique which could cause the values shown here to underestimate the variance of these kinematic measures.

CONCLUSIONS

The relationship between two lifting task parameters (load weight and starting height) and the variance of trunk kinematic variables and ground reaction forces were explored during a laboratory study of a repetitive lifting task. The results showed that the starting height impacted the variance of the sagittal plane kinematic variables and the peak vertical ground reaction forces, while the magnitude of the load lifted affected only the peak shear ground reaction force. These findings demonstrate that understanding both the mean response as well as the variance of the response may provide key insights into the risk posed by occupational lifting tasks.

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